Operation and Economics for Storage in Electricity Markets

——The China Perspective

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Energy Internet Research Institute of Tsinghua University

- THEIRI was started preparing in 2014, and established on April 24, 2015
- THEIRI aims move forward development of Sci & Tech and industrialization of Energy Internet, with research on:
  – Energy Internet Strategy
  – Energy Internet Key Technology & Standard
  – Energy Internet Fundamental Science

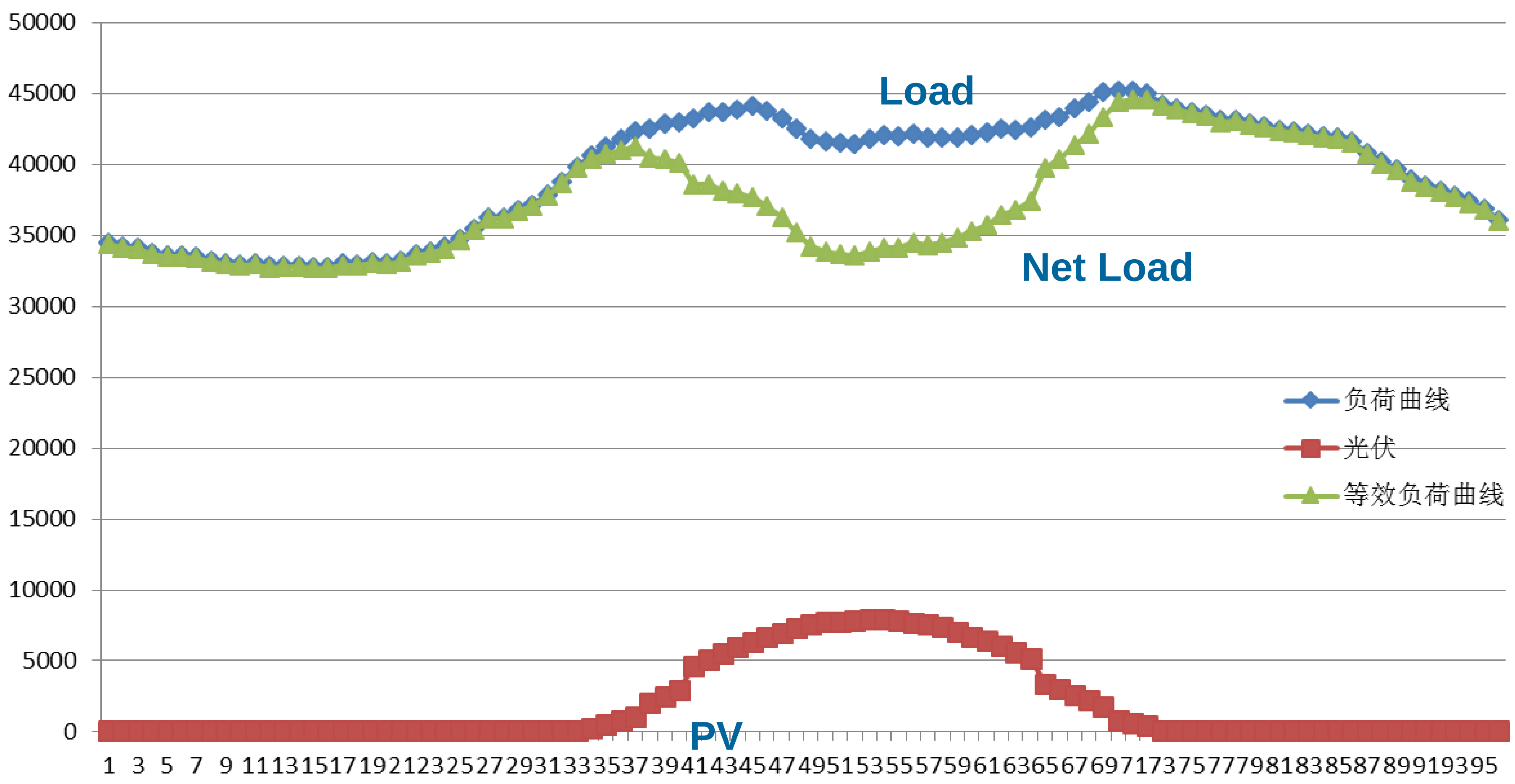
through:

  – International Research collaboration
  – Inter-discipline Research collaboration

Facts on China's PV Industry

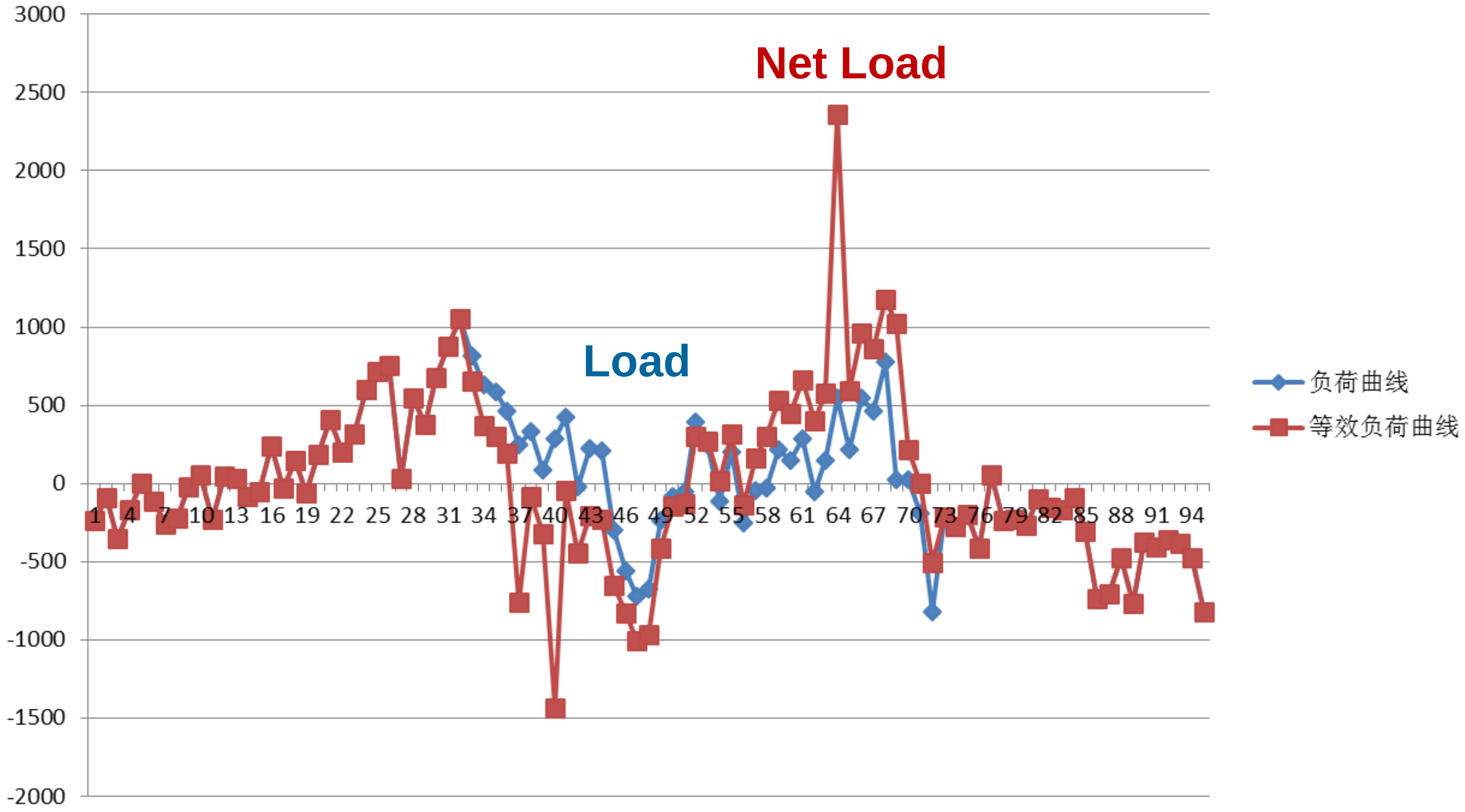
- **PV Capacity**: 77 GW (43 GW in 2015, 80% increase in 2016), accounts for 5% and 1% in capacity and generation Mix for the country
- **Distributed PV Capacity**: 10 GW, 13% for PV capacity.
- **PV Curtail Rate**: 20%, mainly in Northwest region. 32% in Xinjiang Province. (Trans bottle-neck and lack of flexibility)
- **Policy**: 0.064 $/kWh subside for distributed PV (plus the local benchmark price of coal), and fixed price for PV station (0.1-0.13 $/kWh), **twice** compared to the benchmark price for coal-fired power plant (0.05-0.07 $/kWh)
- **Good Case**: Qinghai, max load 11 GW (6 GW PV), 168 hours continuous zero-carbon emission electricity supply.

China’s Duck Curve



- 20% of PV in a regional power grid of China, planned in 2020 (maybe faster).

China’s Duck Curve



- 20% of PV in a regional power grid of China, planned in 2020 (maybe faster).
- Twice Minute fluctuation: 1056 VS 2357 -821 VS -1438 (by simulation).

Outline

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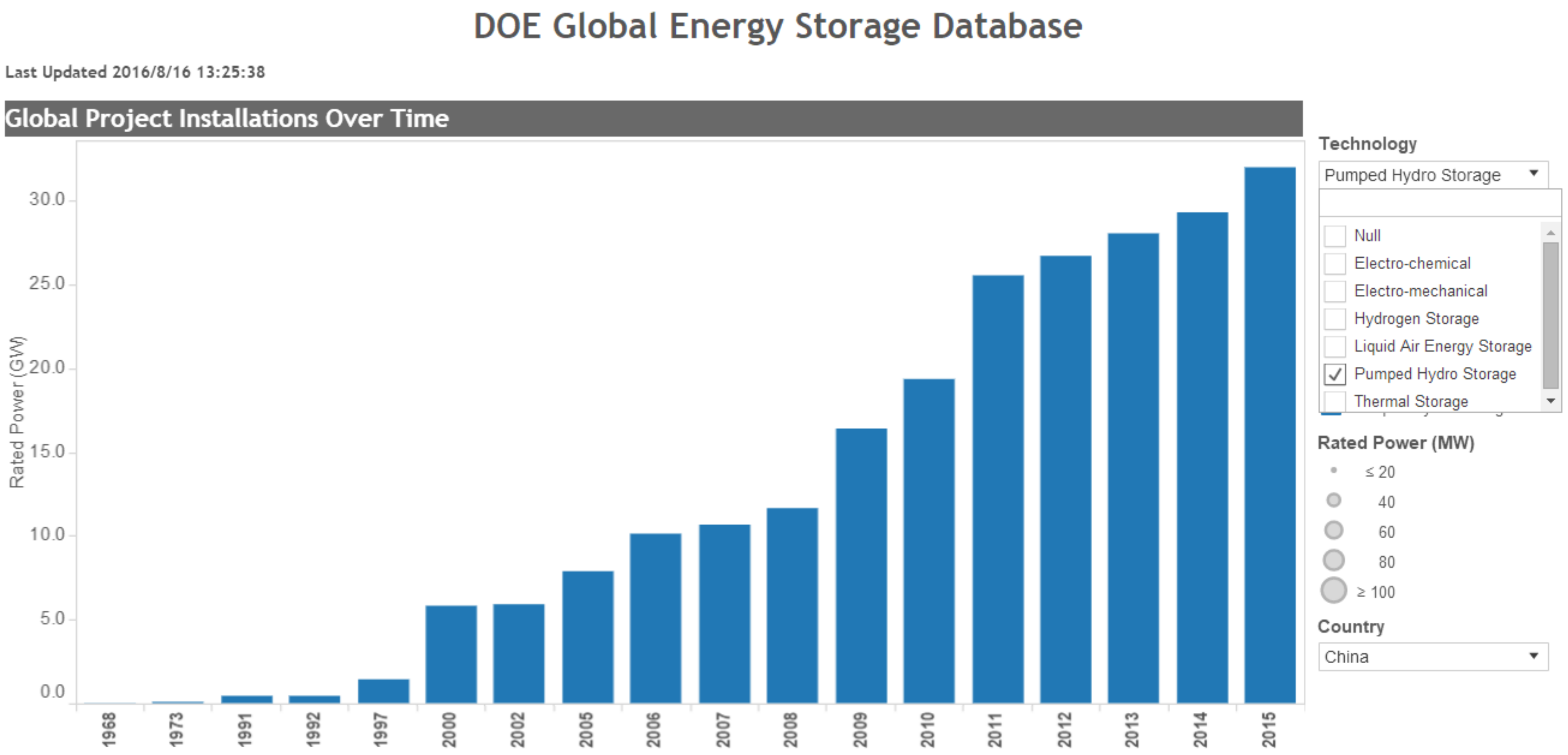
- **Storage Development in China**
- Cost and Economics
- Value and Business Model
- Operation in the Market

Energy storage scale in China



- According to the statistics of DOE, China has installed more than 30GW energy storage utilities by the end of 2016, most of which pump hydro （ **~20%** ）.
- The scale of electro-chemical storage (battery) is about 180 MW by the end of 2016 （ **5%+** ）.
- Capacity of EV battery is about **5-6 GW** (Li-ion), utilize usage battery develop relatively slow in China

Typical energy storage project in China

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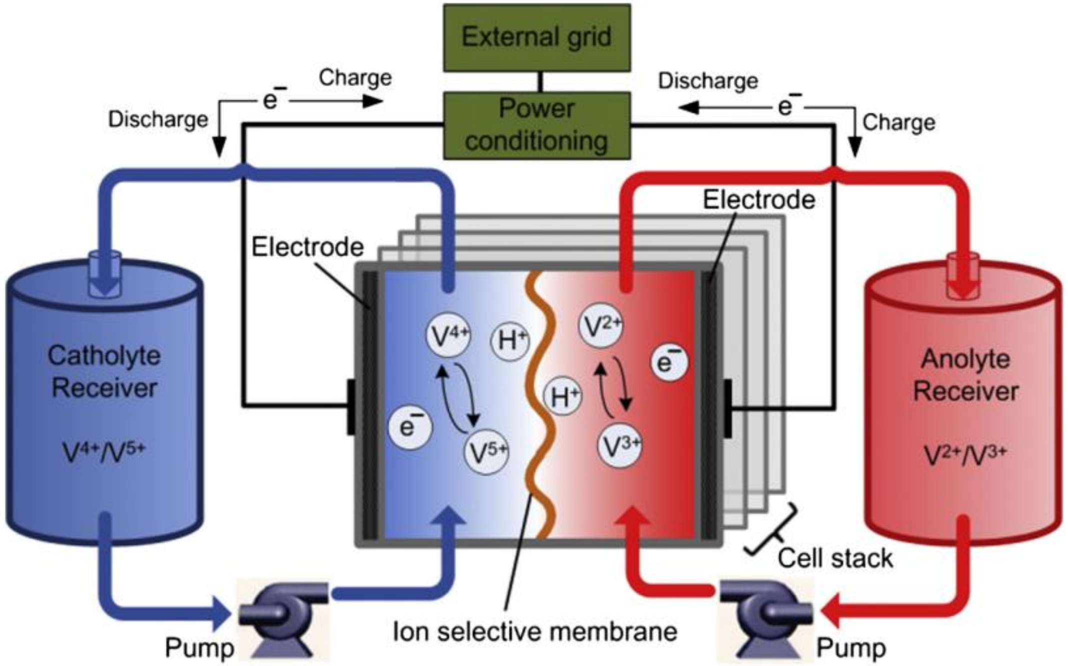


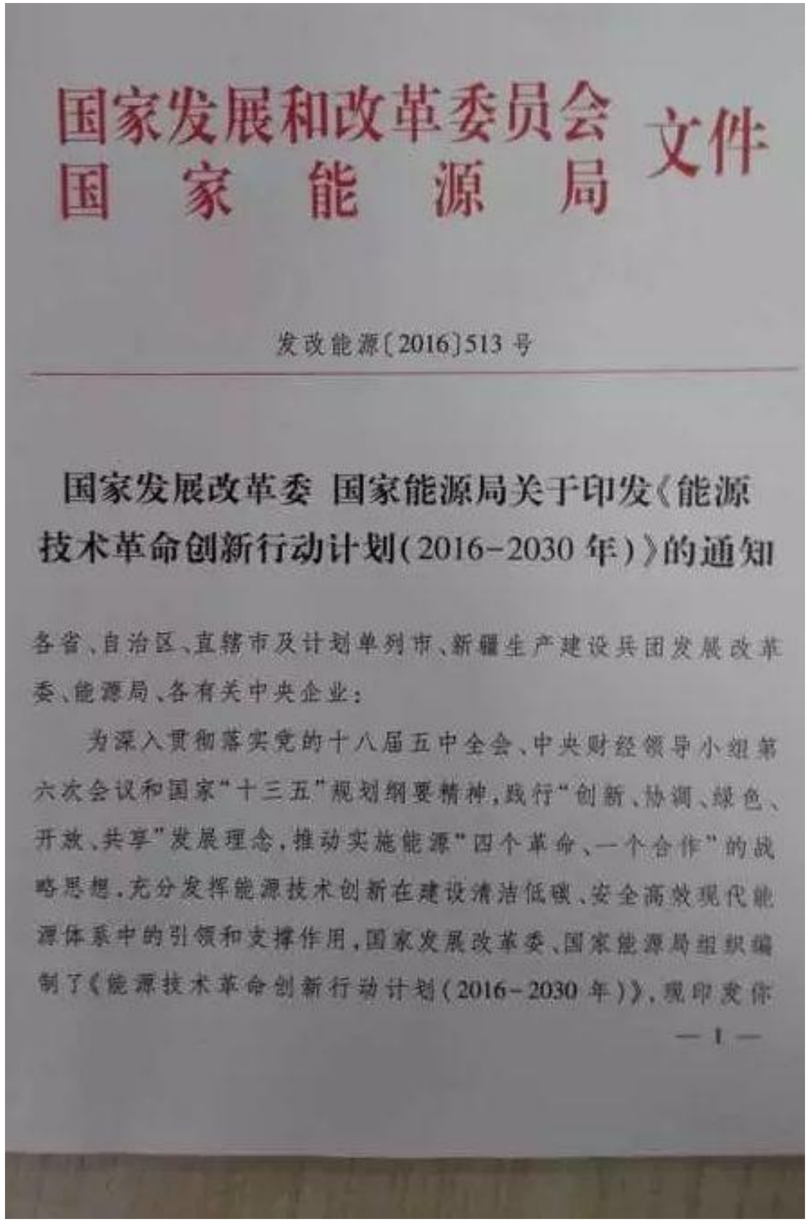
Woniushi VRB project, Liaoning, China

- 5MW, 2h VRB (Vanadium Redox Battery) energy storage system in Liaoning.
- The project is constructed for the effective usage of wind power.
- A 200MW-4h project is under construction （ **Liaoning** , probably the **biggest** one) .

Energy storage supporting policy in China

Policy	Government agency	Time
Strategic Action Plan for Energy Development	The State Council	Nov.2014
Promoting Development of Pumped-hydro Power Station	National Development and Reform Commission	Nov.2014
New Round Power Industry **Deregulation Reform**	The CPC Central Committee and State Council	Mar.2015
Promoting the Development of "**Internet Plus**" Smart Energy	National Development and Reform Commission	Feb.2016
Promoting Energy Storage Supplying **Ancillary Service** in the "**N**orth, **N**orthwest and **N**ortheast" Regions (**3-N**)	National Energy Administration	Mar.2016
Energy Revolution Innovation Action Plan (2016-2030)	National Development and Reform Commission	Apr.2016
National Innovation-driven Development Strategy	The CPC Central Committee and State Council	May.2016
The 13th "**Five-year Plan**" for the Development of Strategic Emerging Industries	The State Council	Nov.2016
The 13th "**Five-year plan**" for Renewable Energy Development	National Development and Reform Commission	Dec.2016
The 13th "**Five-year plan**" for Energy Technology Innovation	National Energy Administration	Jan.2017
Promoting Energy Storage Technology and Industrial Development (draft)	National Energy Administration	Mar.2017

Energy storage supporting policy in China



国家发展和改革委员会 文件
国 家 能 源 局

发改能源〔2016〕513 号

国家发展改革委 国家能源局关于印发《能源技术革命创新行动计划(2016-2030 年)》的通知

各省、自治区、直辖市及计划单列市、新疆生产建设兵团发展改革委、能源局、各有关中央企业:

为深入贯彻落实党的十八届五中全会、中央财经领导小组第六次会议和国家"十三五"规划纲要精神,践行"创新、协调、绿色、开放、共享"发展理念,推动实施能源"四个革命、一个合作"的战略思想,充分发挥能源技术创新在建设清洁低碳、安全高效现代能源体系中的引领和支撑作用,国家发展改革委、国家能源局组织编制了《能源技术革命创新行动计划(2016-2030 年)》,现印发你

— 1 —

- High Temperature Thermal Storage
- Large Scale Energy Storage
- Hybrid Energy Storage
- New Concept Energy Storage
- Electro-chemistry Energy Storage

➢ Energy storage technology embodies core competitiveness, would be support greatly.

Energy storage supporting policy in China

High Energy Density

Long Life

Low Cost

Rapid Charge Ability

Environmentally Friendly

High Security

- In 2016, China's new energy automobile ownership increased more than **80%**, to **1.1 m**. (50% and 2 m globally). It means **80%** of the increase is in China. The same trend could be expected in 2017.

Business model of energy storage in China

国 家 能 源 局

关于征求《国家能源局关于推动电储能参与“三北”地区调峰辅助服务工作的通知（征求意见稿）》意见的函

国家能源局文件

国能监管[2016]164号

国家能源局关于促进电储能参与“三北”地区电力辅助服务补偿（市场）机制试点工作的通知

- Peak-shaving and regulation with energy storage technology is being experimented, storage is admitted to provide ancillary services and get reasonable payment.
- Demand side response with energy storage would be experimented in north, east and south China.
- Peak and off-peak power price difference, as well as demonstration of regulation effort, are significant to the economics of storage.

Energy storage prospect in China

中共中央文件

中发〔2015〕9号

中共中央　国务院
关于进一步深化电力体制改革的若干意见
（2015年3月15日）

- "Bilateral + Spot" market system will be established.
- Energy storage would become a promising participant in energy and ancillary market, especially considering the increasing of intermittent renewables.

Energy storage prospect in China

微门户

中华人民共和国国家发展和改革委员会
National Development and Reform Commission

请输入关键字

热门搜索：PPP 油价 新

首页 > 政策发布中心 > 通 知

关于推进“互联网+”智慧能源发展的指导意见

发改能源[2016]392号

各省、自治区、直辖市及计划单列市、新疆生产建设兵团发展改革委、能源局、工业和信息化主管部门，各有关中央企业：

“互联网+”智慧能源（以下简称能源互联网）是一种互联网与能源生产、传输、存储、消费以及能源市场深度融合的能源产业发展新形态，具有设备智能、多能协同、信息对称、供需分散、系统扁平、交易开放等主要特征。在全球新一轮科技革命和产业变革中，互联网理念、先进信息技术与能源产业深度融合，正在推动能源互联网新技术、新模式和新业态的兴起。能源互联网是推动我国能源革命的重要战略支撑，对提高可再生能源比重，促进化石能源清洁高效利用，提升能源综合效率，推动能源市场开放和产业升级，形成新的经济增长点，提升能源国际合作水平具有重要意义。为推进能源互联网发展，根据《国务院关于积极推进“互联网+”行动的指导意见》（国发[2015]40号）的要求，提出如下意见。

- ➢ Energy Internet will integrate the multi-energy system (Electricity, Gas, Heat, Cooling , Trans…).
- ➢ Energy storage plays a significant role in the construction of energy internet (decoupling power supply – grid - load).

Energy storage prospect in China

Tsinghua University

	2016	2020	2025	2030
Utility scale	~30GW	~50GW	~90GW	~160GW
Automobile requirement	~25GWh	~75GWh	~350GWh	~1500GWh
Unit cost	~100%	~80%	~60%	~50%

➢ Energy storage industry would grow rapidly in China in the next decades.

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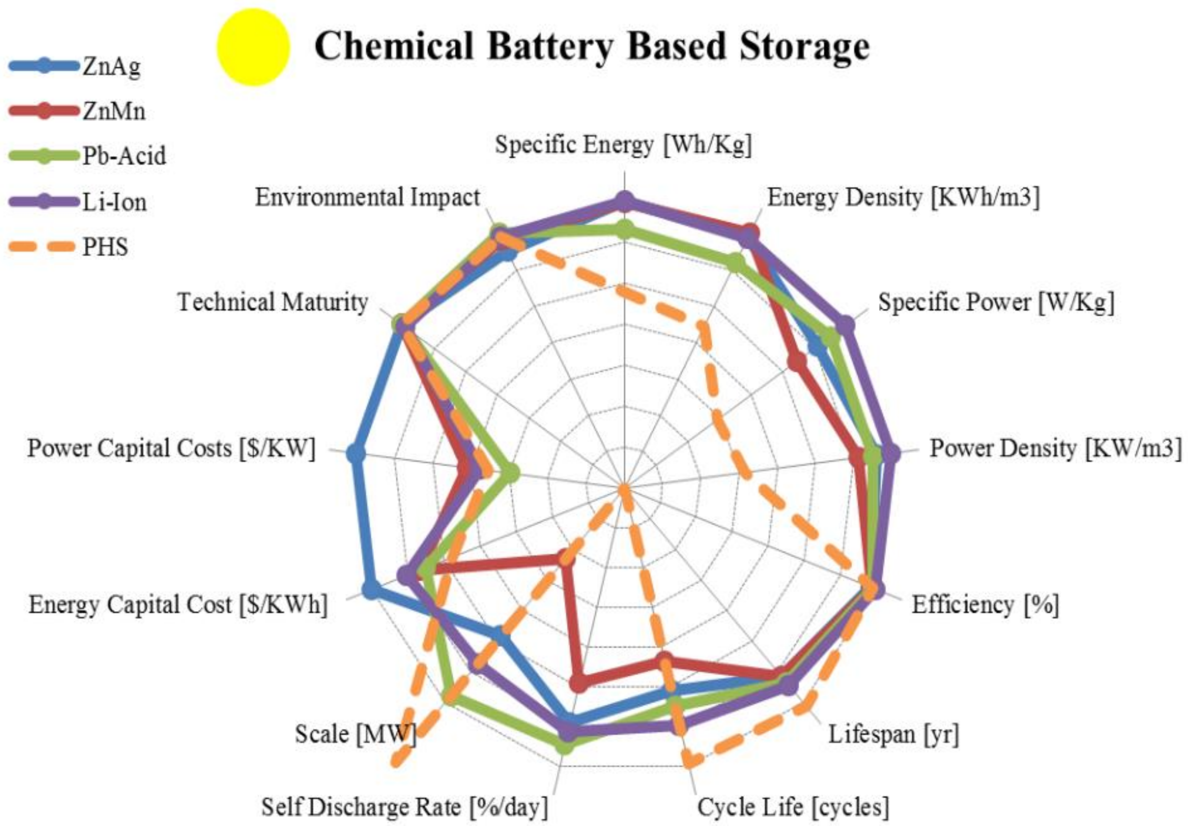
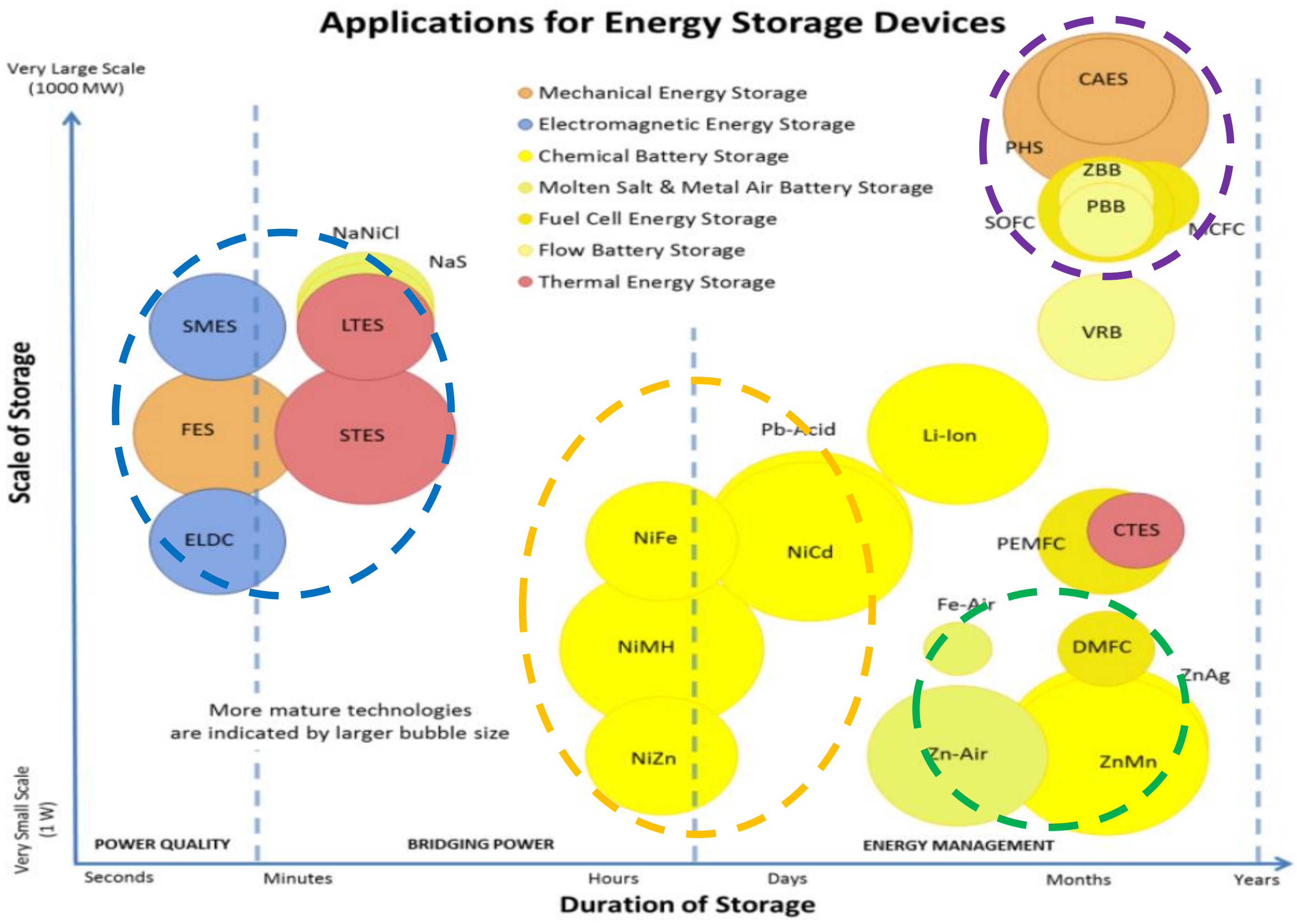
Metrics of energy storage technologies



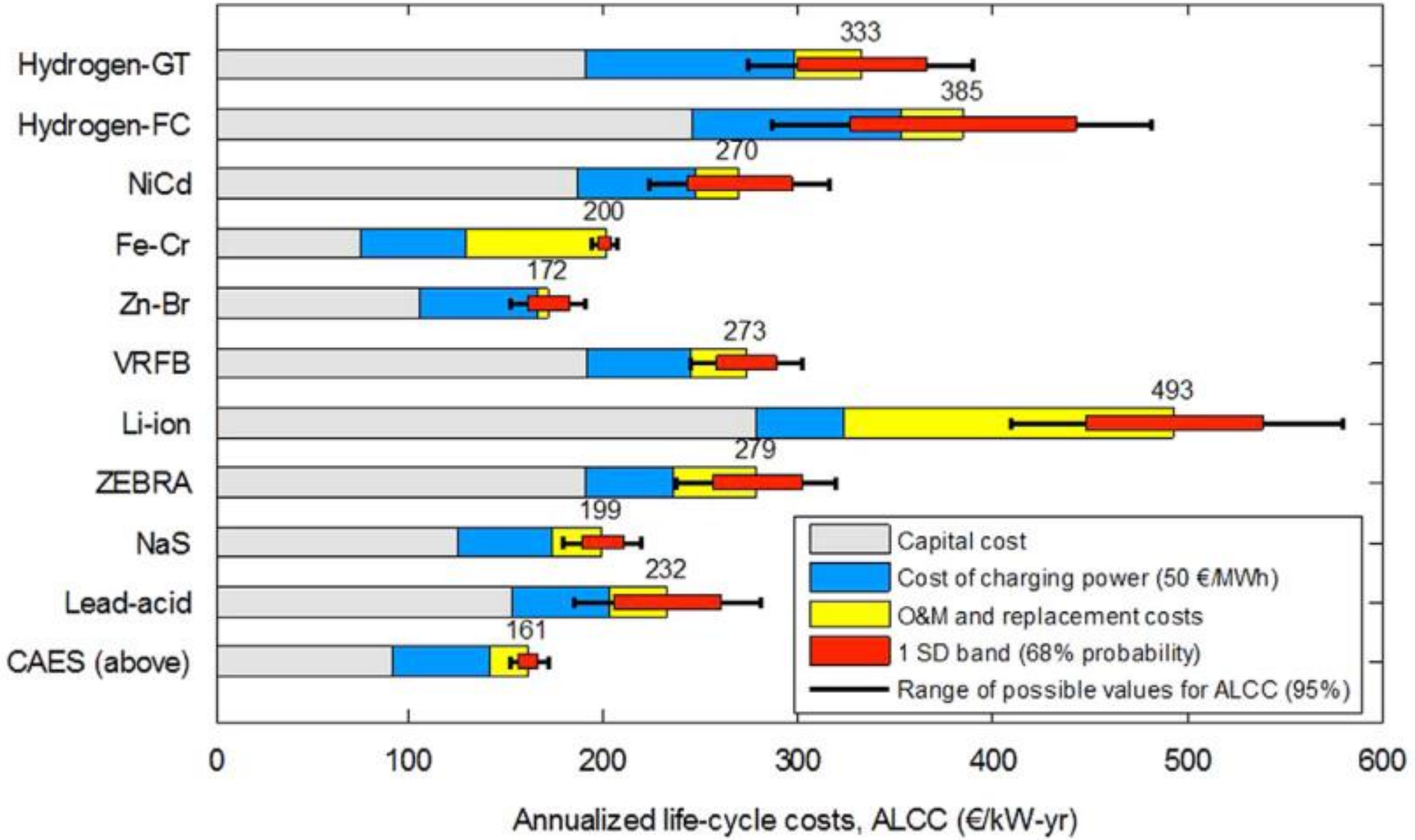
- Technology comparisons are made with respect to energy, power, efficiency, lifespan, cycle life, self-discharge rate, scale and cost. Application, technical maturity and environmental impacts are also considered.
- It is impossible that one energy storage technology perfect meets all technical requirements.

Scale and Duration – most important



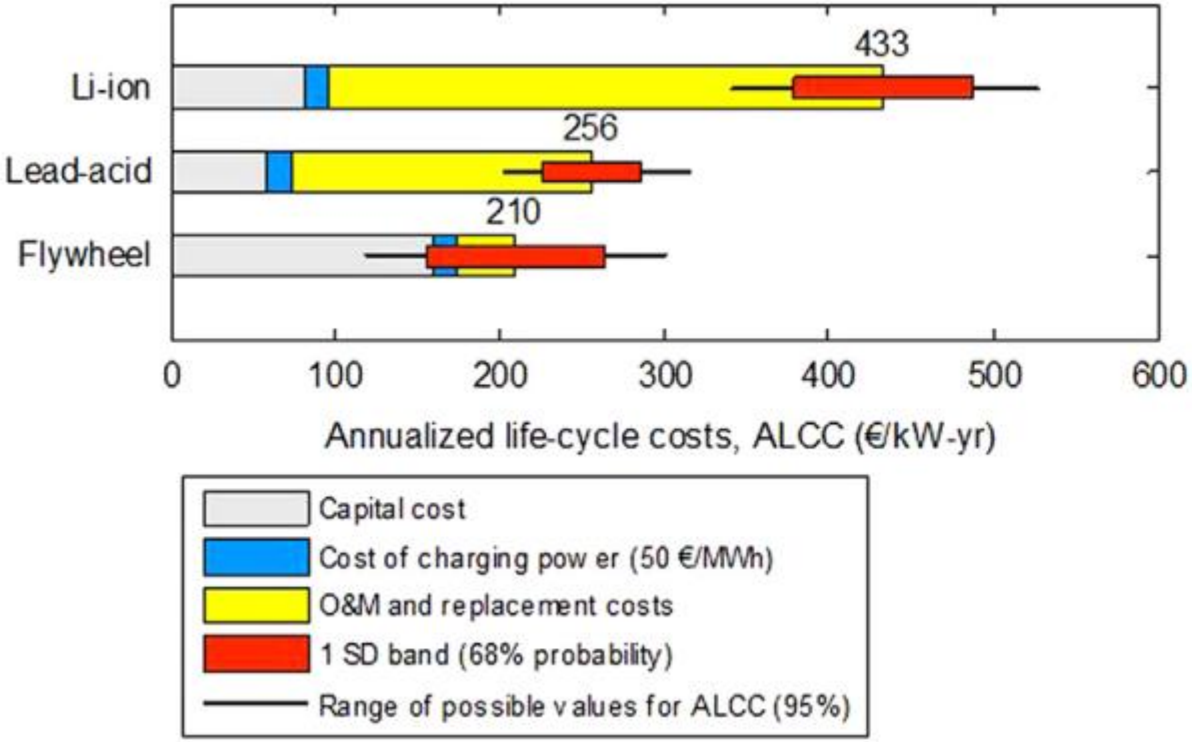
- Scale from W to GW, duration from seconds to months or longer.
- From users side, technologies can be roughly divided into four groups: large scale-energy, common, power, small scale-energy.

Cost – for energy usages (T&D support)



- The annualized life cycle costs (ALCC) of EES systems and related uncertainty for T&D support applications, with 400 cycles per year, 8% interest rate and 2 hours discharge time. Data collected from years 2010 to 2014.
- Compressed air is limited by geography conditions, Li-ion now becomes cheaper.

Cost – for power usages (regulation)



- The annualized life cycle costs (ALCC) and its uncertainty for EES systems applicable in frequency regulation and power quality services, 1000 cycles per year, 8% interest rate and max 15 min discharge time.
- Comparing to energy usages, cost rate of charging reduces.

Outline

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Values of energy storage

Capacity Values	Energy Values	Service Values
Power plant upgrade deferral	Peak shaving	Frequency regulation
Transmission upgrade deferral	Emergency energy supply	Back up service
Renewable energy Integration	Renewable energy storage	Voltage service
Ride-through capacity	Load levelling	Power quality
Demand response		Black start

Values of energy storage

Market members	Energy storage values	Technologies
Power plant companies	Power plant upgrade deferral Peak shaving & frequency regulation Avoid extremely low electricity price	Pump hydro, compressed air, thermal storage, batteries
Grid companies	Transmission upgrade deferral Transmission and distribution stablization Peak shaving & frequency regulation & voltage support Back up & Black start & power support	Pump hydro, compressed air, thermal storage, batteries, supercapacitor, flywheel
Renewable companies	Renewable energy storage Improve power quality Avoid electricity deviation punishment Avoid extremely low electricity price	thermal storage, batteries(or purchase third party service)
Users/ electricity sellers	Arbitrage Support ancillary service Support renewable energy Avoid extremely high electricity price Stable electricity supply	Mostly batteries

Business models – energy and ancillary service

国家能源局文件

国能监管[2016]164号

国家能源局关于促进电储能参与“三北”地区电力

辅助服务补偿（市场）机制试点工作的通知

200MW/800MWh vanadium redox flow battery, Dalian city, Liaoning Province, Northeast China

Storages are officially encouraged to participate the ancillary service markets in the north area of China

- Peak shaving, load following and energy management.

Business models – energy management

Pumped storages in China, for energy management , regulation and renewable following.

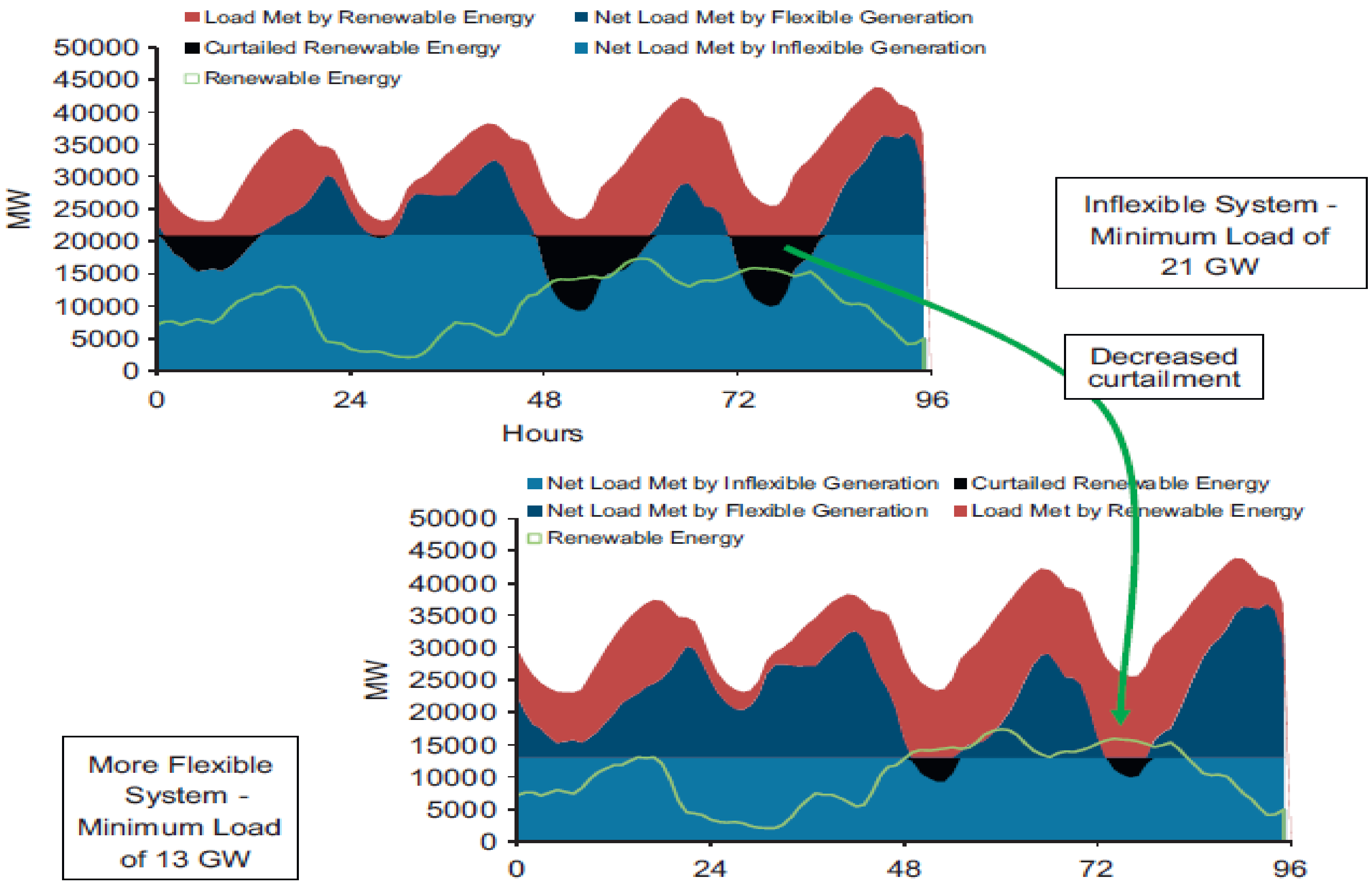
- The grid corporations and power generation companies jointly invest the pumped storages.
- The ratio of investments is usually : grid corporations 50%, some generation companies 50%. The usage charge are also apportioned between the grid and generation companies.
- Two-part payment: Capacity payment plus Energy payment.

Business models – renewable energy synergy

Li-ion battery system in Hebei Province, China

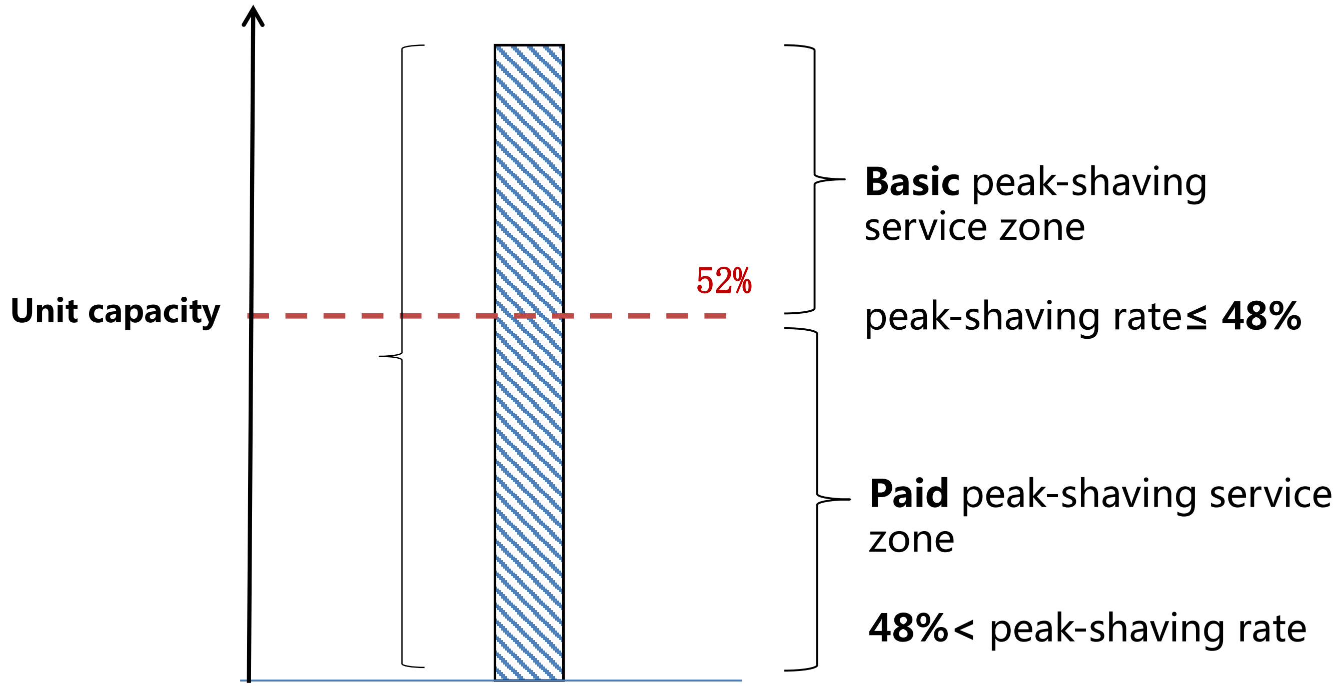
- 95 MW Li-ion battery system, including 1402 battery cupboards.
- The largest demonstration project consists of 500 MW wind power, 100MW solar power, storages and transmission systems.

Business models – peak-shaving market



Business models – peak-shaving market

The market balance of basic peak - shaving duty



Peak-shaving rate 48% is calculated which accord with physical truth of Northeast power grid.

The rate both ensures the role of economic leverage in market operation and doesn’ t make destructive impact on business operations.

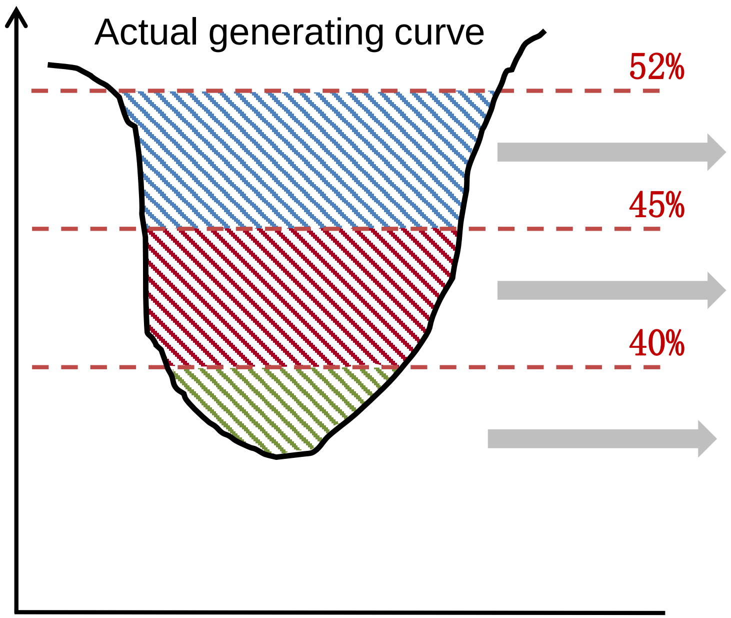
As a variable parameter, it can be dynamical regulated by northeast energy regulatory agency according to the actual operation of the market.

Business models – peak-shaving market

Calculation of deep peak-shaving compensation

Assume a power plant A with generating curve below, which provides deep peak-shaving service. Its compensation is calculated by three level compensations added together, each determined by corresponding peak-shaving electric quantity and actual clearing price of electricity.

Load rate of power plant A



First peak-shaving electric quantity * First actual clearing price of electricity

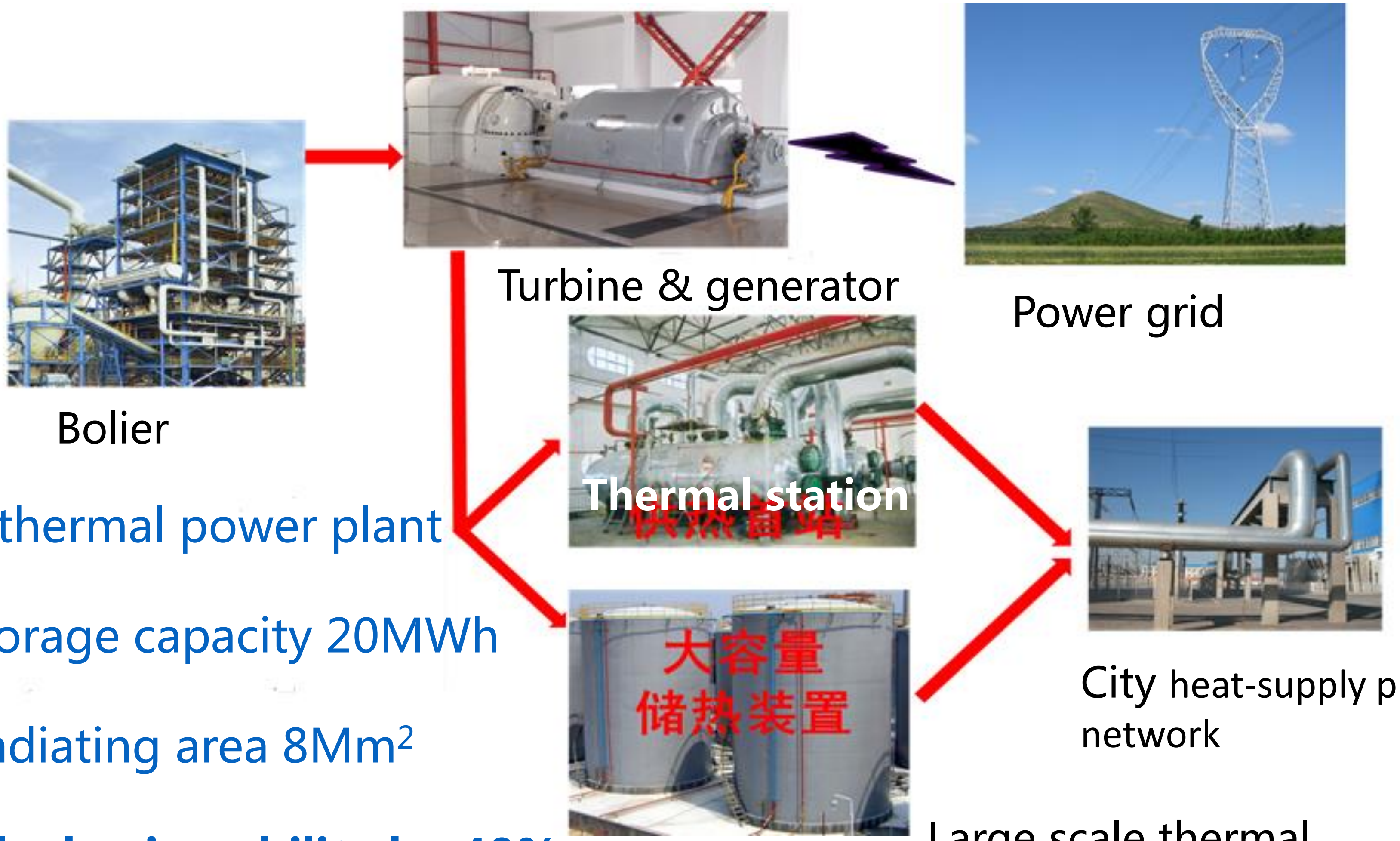
Second peak-shaving electric quantity * Second actual clearing price of electricity

Third peak-shaving electric quantity * Third actual clearing price of electricity

Total peak-shaving compensation

Business models – peak-shaving market

Develop energy storage device for power plant, in order to increase regulating ability and improve clean energy absorption ability.



Fengtai thermal power plant

Thermal storage capacity 20MWh

Heat radiating area 8Mm^2

Improve peak-shaving ability by 40%

Business models – frequency regulating service

- **Resources for regulating market: (FERC Order 755)**
  - Resources limited by ramping: RegA, support traditional/slow signals
    - generators：steam, hydro, gas turbine, combined cycle units
  - Resources limited by energy: RegD, support dynamic/rapid signals
    - Energy storage：battery, fly wheel
    - Behind-the-meter Storage：water heater, battery, plug-in hybrid electric vehicle
    - Demand response：variable-speed pump, ceramic heat reservoir

Business models – frequency regulating service

Lithium battery, from Ray Power Technology, Beijing

- Lithium battery storages, 9MW, located in the Jingyu, Yangguang and Hengbei power plants, respectively, in **Shanxi Province**, China, for frequency regulation.

Business models – distribution usage

lithium battery storage systems

- Lithium battery, 1MW*4h, DC 700V, 2 500kV PCS, located in **Shenzhen city**, belonging to the China Southern Power Grid, for peak shaving, regulation, research and energy management in the distribution level.

Business models – control the load deviation

Storages system in Guangdong Province, China

- Electricity retailers use energy storage systems in Guangdong Province, for controlling the demand deviation of their power consumers and avoiding the deviation penalty.

Business models – capacity market

- **Resources for capacity market**
  - Traditional generator capacity
    - Thermal, hydro, nuclear, wind
  - Transmission capacity expansion
  - Demand side resource（energy storage, virtual power plant, demand response
  - Promotion of energy efficiency（energy-conserving electric appliance）
- **Energy storage take part in the market**
  - Support capacity service（response system emergency capacity support instructions and meet technical requirements）
  - Revenue reaches 20% compares to generators in capacity market
  - Non-generator capacity provides more than 10% service

Business models – decrease T & D capacity payment

Storages system in the province with two-part tariff, China

- Two part tariff includes the energy price and the capacity price.
- The capacity price is determined by the power demand used by the consumers.
- Users could apply the storages to decrease their maximum demand and the charges.

Outline

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- Storage Development in China
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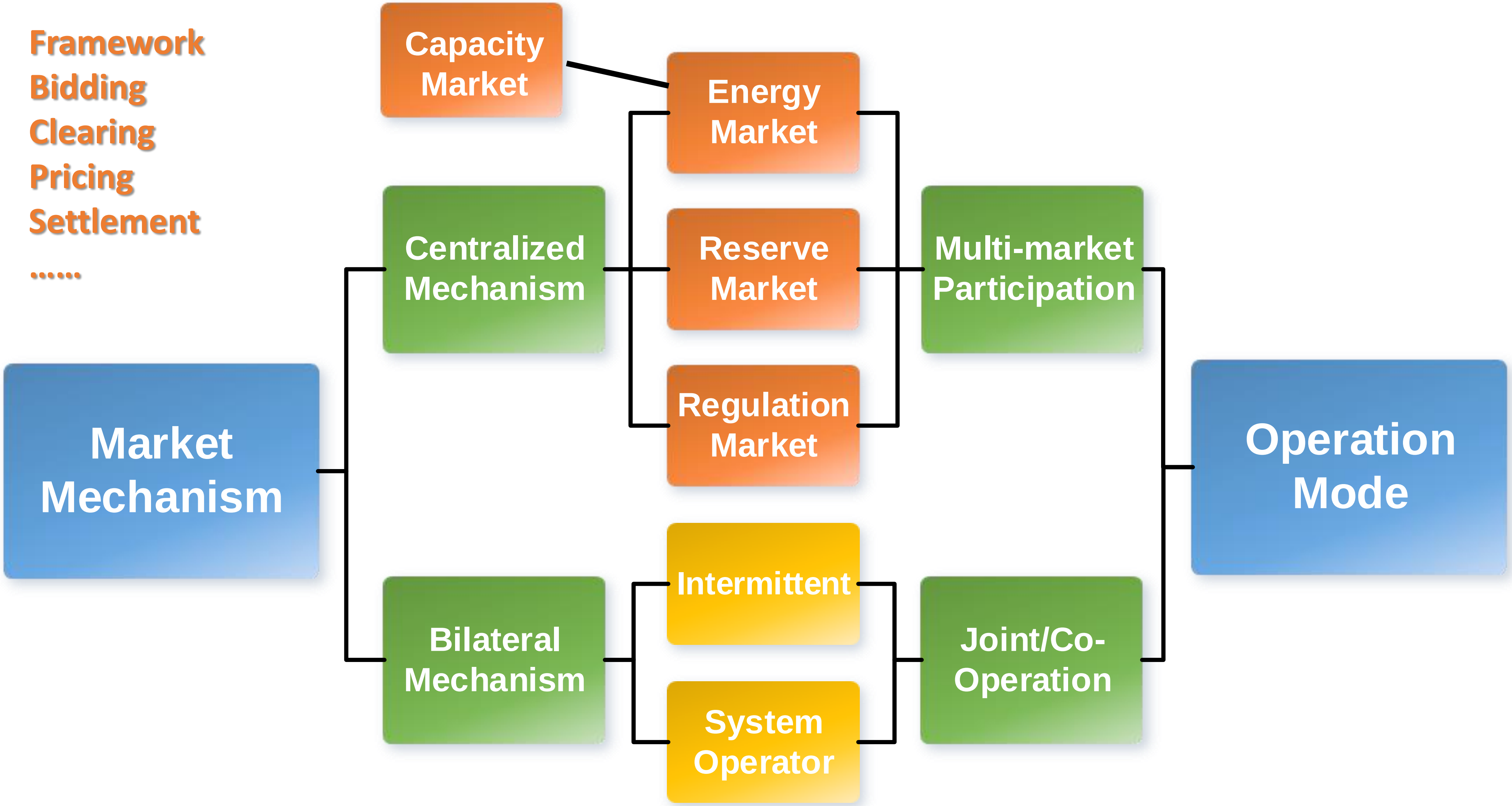
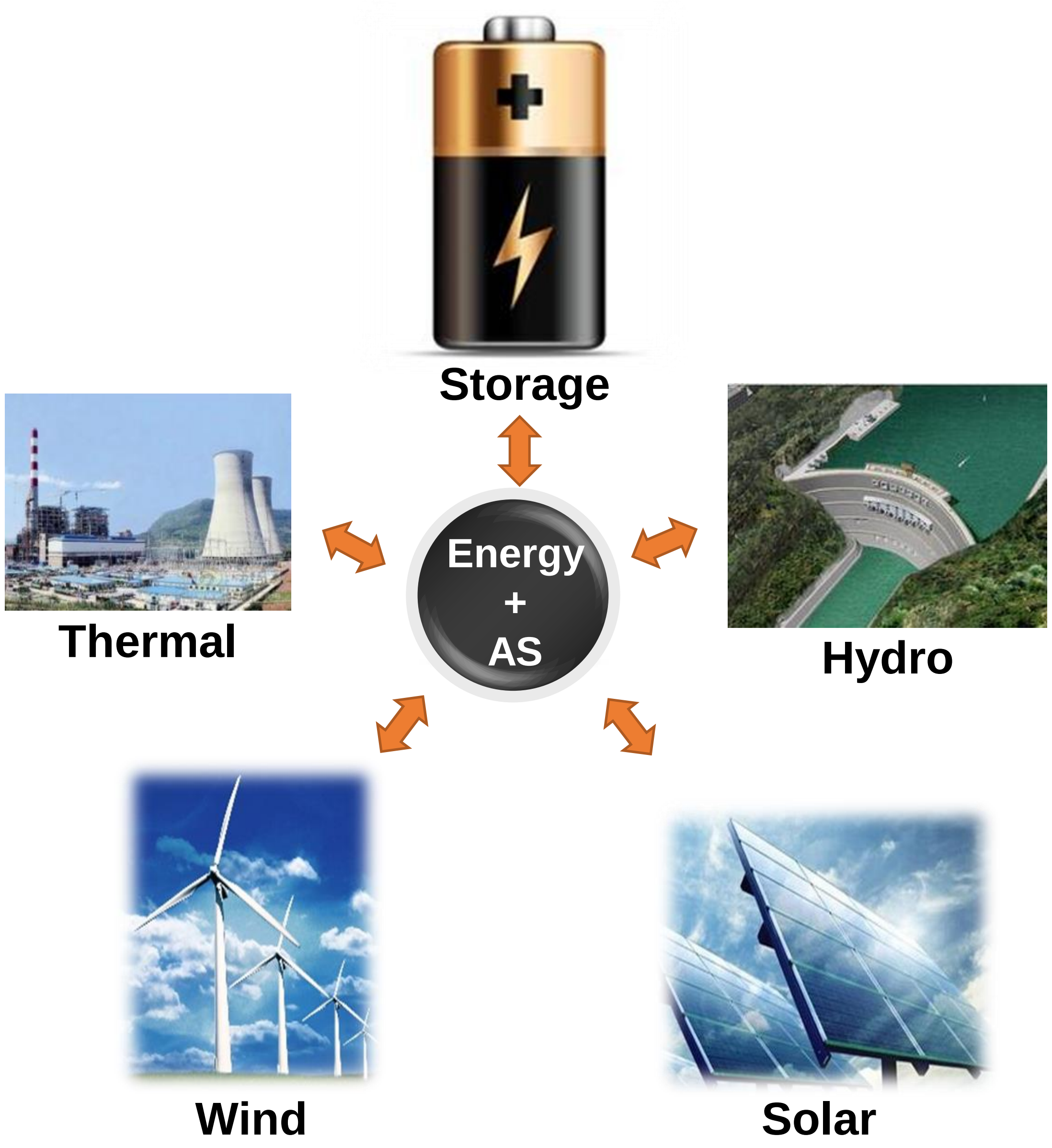
- **Operation in the Market**

Market Mechanism and Operation Mode

Framework
Bidding
Clearing
Pricing
Settlement
……



Perspective



I. Storage Operator:

Optimal Bidding Strategy

II. VPP Operator:

Cooperation Strategy

III. System Operator:

The Impact of Storage’s Strategic Bidding on the Market Equilibrium

Key Concerns of Self-Operation

1 Benefit

- Joint Bidding in combined market
- Pay for performance
  - FERC Order 755
  - two-part payment
  - mileage
  - dynamic regulation signal

2 Cost

- Storage Lifetime
  - frequent charging and discharging
  - depth of discharge
  - cycle life vs. float life
  - capacity deregulation

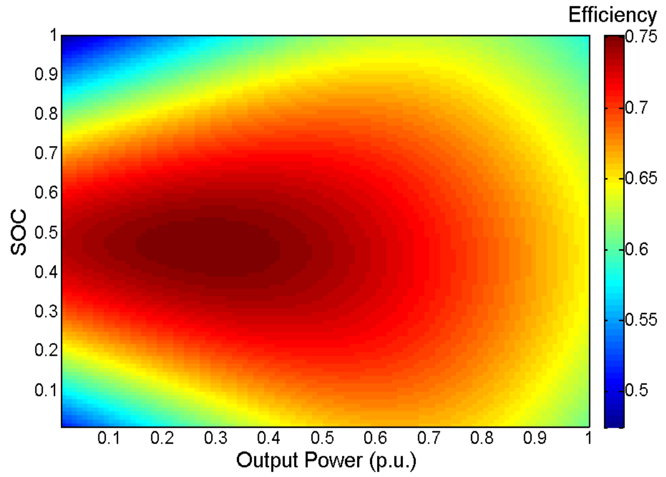
3 Efficiency

- Energy loss cost
  - battery's efficiency not constant
  - relevant with power output and SOC
  - optimal operation strategy

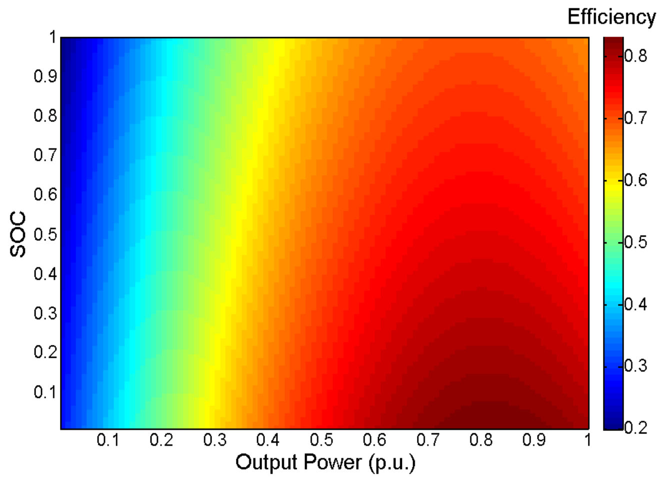
Dynamic Efficiency of Flow Battery

- Motivation
  - The efficiency of battery storage is usually assumed a constant in existing literatures
  - Both charge and discharge efficiency is dynamically dependent on the operating states including output power, state of charge (SOC) and temperature.
- Contribution
  - Reformed the dynamic efficiency of vanadium redox flow battery into the functions of operating states
  - Incorporated the dynamic efficiency functions into the operation optimization model
  - Analyzed the impacts of considering dynamic efficiency on the battery's optimal operating strategy and arbitrage profit

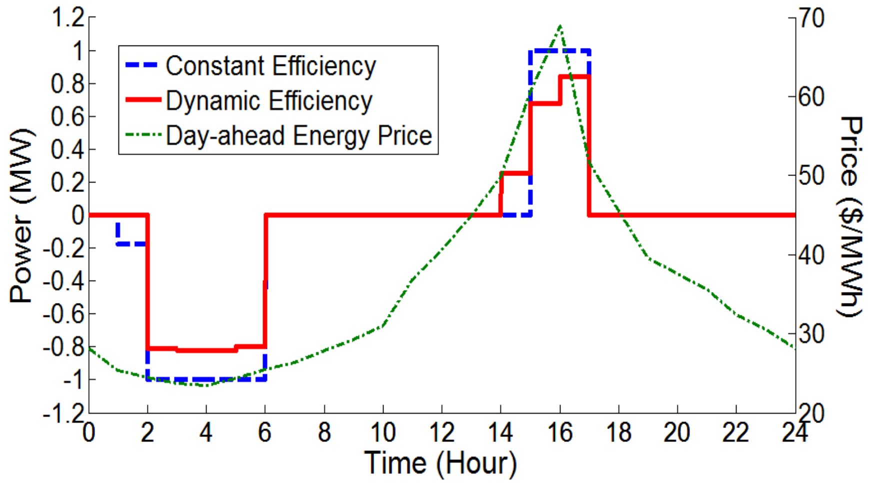
Dynamic Efficiency of Flow Battery



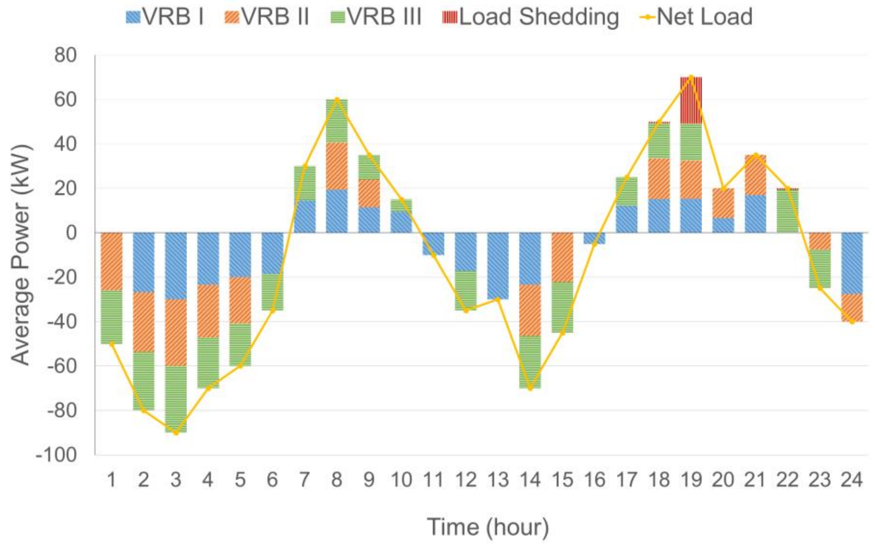
Discharge



Charge



Single Battery Arbitrage



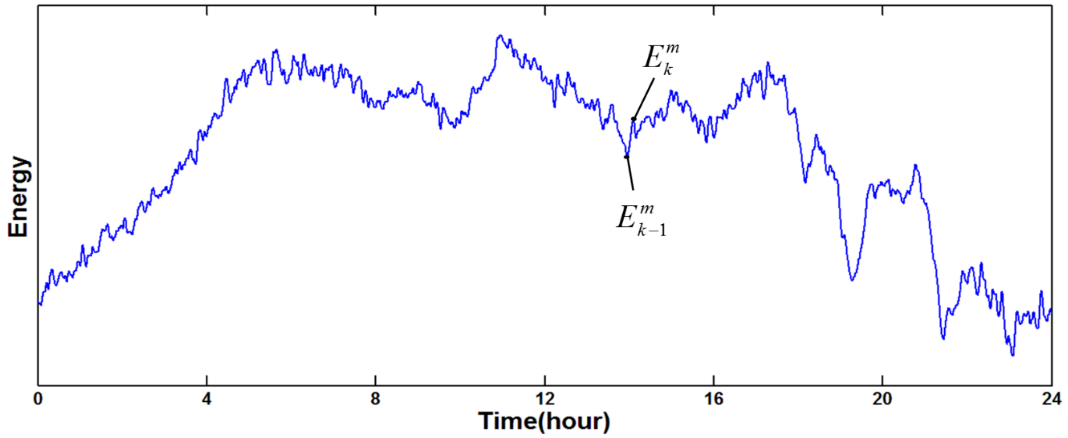
Multiple Batteries in an Isolated Microgrid

- About 50% increase in daily revenue
- About 10% decrease in load shedding

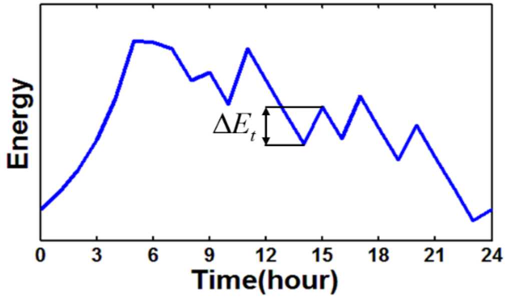
Bidding Considering Battery Cycle Life

- Motivation
  - In frequency regulation application, battery degradation is a key factor to its economic viability
  - To reflect the trade-off between short-term market revenues and total battery lifetime
- Contribution
  - Incorporated a battery cycle life model into the optimal bidding model of battery storage in energy, reserve, and regulation markets
  - Proposed a decomposed cycle life calculation method to reduce the complexity of the model
  - Analyzed the impacts of considering battery cycle life, and the trade-off between short-term market revenues and total battery lifetime

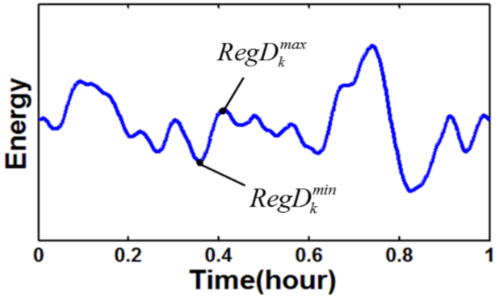
Bidding Considering Battery Cycle Life



Energy curve of battery storage's operation



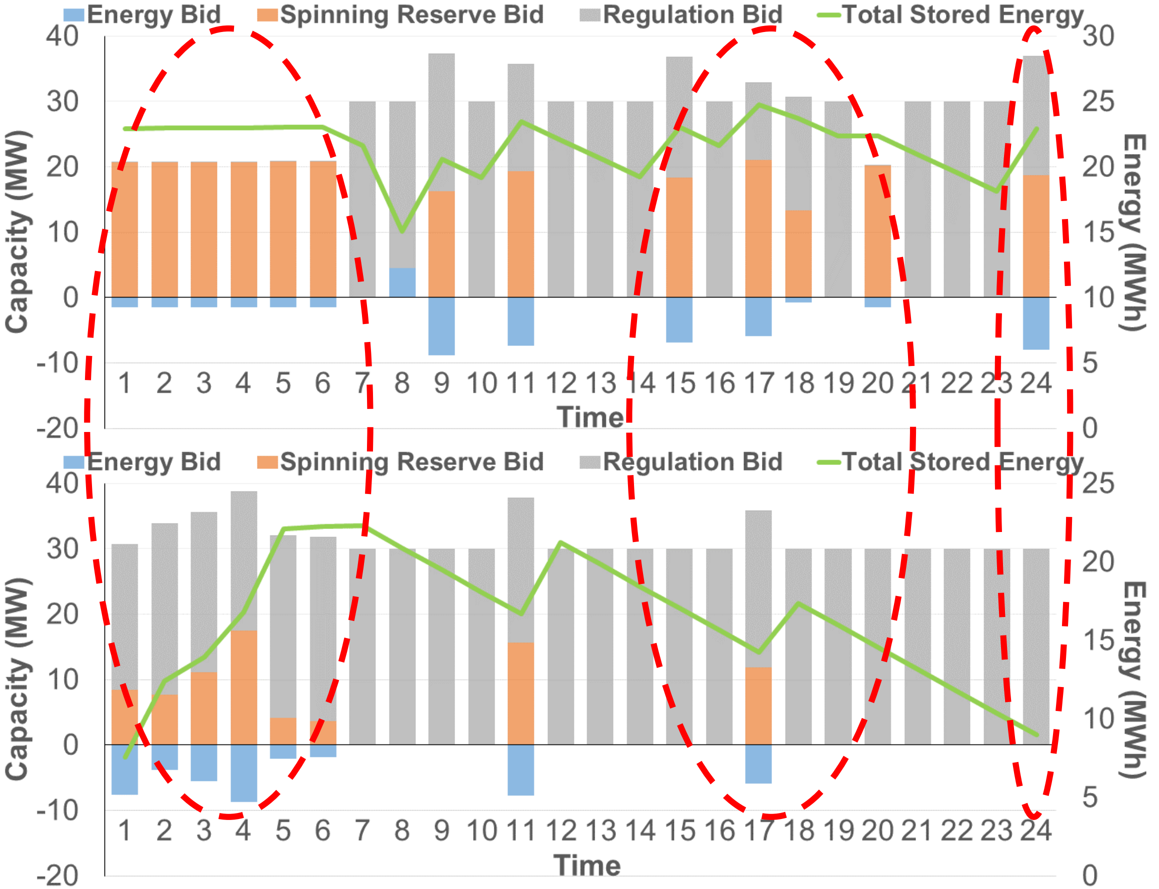
Energy change between hours



Intra-hour energy change

Consider Battery Life

Not Consider Battery Life



- Advantages of the decomposition method:
  - The decision variables (capacity bids) are separated from extreme point picking
  - Enables the model to be solved by commercial solvers because the local extreme points only serve as parameters

- About 30% increase in total revenues

Key Concerns of Cooperation with Intermittent

1 Uncertainty

- Market Price
- Wind & Solar Power
- Modelling Approach
  - Deterministic (Expected Value)
  - M-Scenario Stochastic
  - Robust

2 Flexibility

- How to optimally allocate flexibility to address uncertainty?
- Trade-off between:
  - Energy & ancillary services
  - Supply to the system & reserve to itself

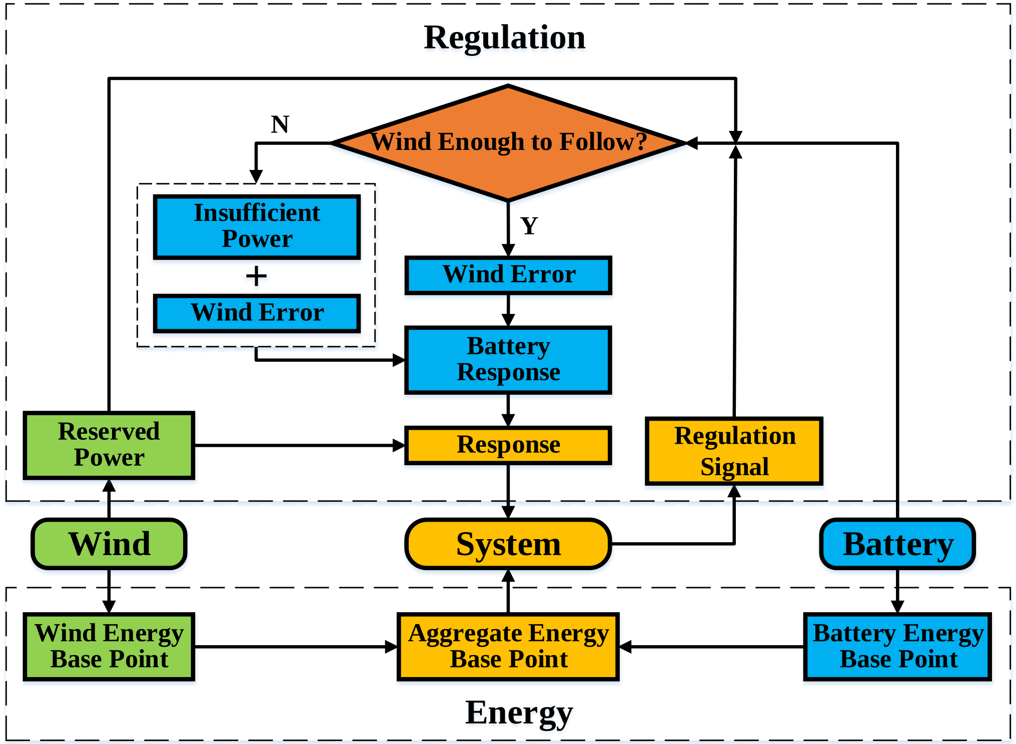
3 Complementarity

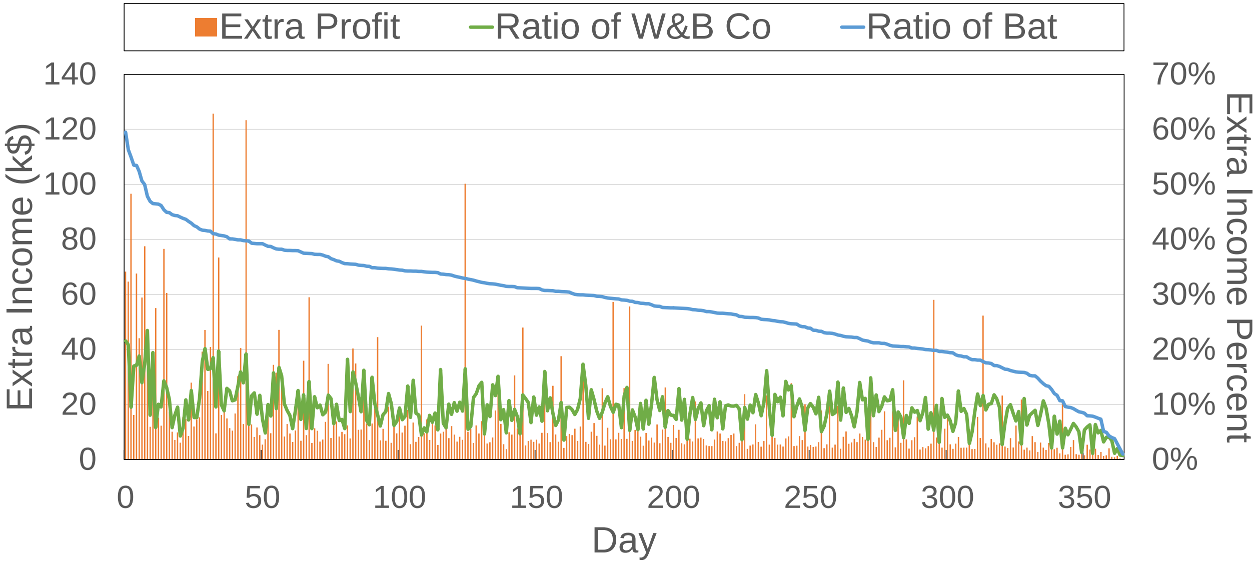
- Aspects that energy storage and intermittent energy complement each other
  - Flexibility
  - Durability
  - Accuracy
- Cooperating scheme and strategy to exploit these aspects

Cooperation of Wind and Battery for Regulation

- Motivation
  - In the application of secondary frequency regulation, wind power and battery storage apparently exhibit complementary characteristics in accuracy and durability
  - Properly designed cooperation strategy can take advantage of the characteristics
- Contribution
  - Proposed a cooperation scheme that employs wind power to track the regulation signal priority, and battery storage to compensate for insufficient and inaccurate power for the purpose of preserving battery cycle life
  - Formulated a simulation model of the real-time battery operation under the proposed cooperation scheme, which calculate the cycle number and energy change of battery over the whole simulation period
  - Proposed an optimal bidding model for wind power and battery storage in joint energy and regulation markets implementing the proposed real-time cooperation

Cooperation of Wind and Battery for Regulation





W&B Co. Income (mil. $)	Battery Income (mil. $)	Extra Income (mil. $)	Ratio to W&B Co.	Ratio to Battery
57	18	5	9%	30%

- To reserve battery life, utilize the reserved wind power in priority
- To assure regulation performance, battery compensates the wind control error and insufficient power

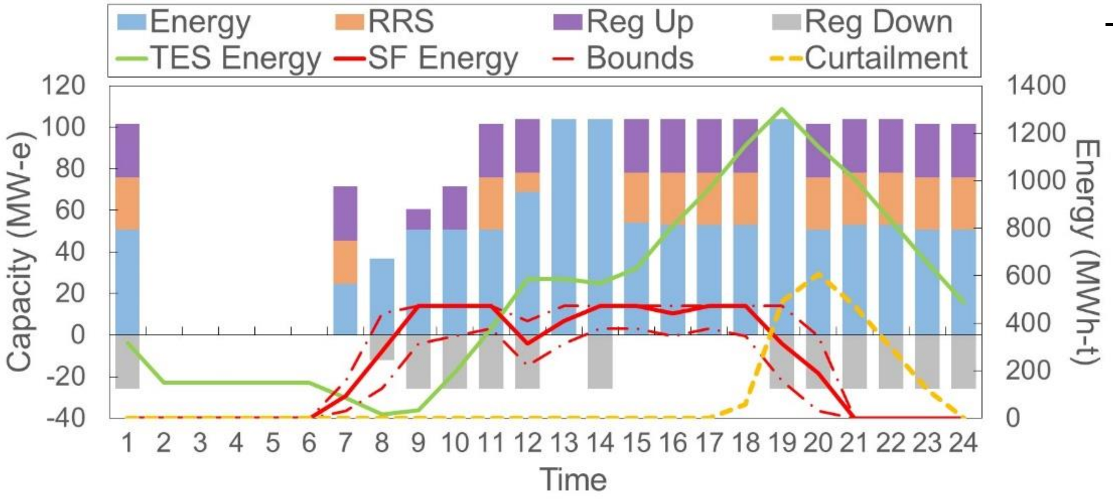
- Another 30% increase in total battery revenues

Offering Strategy for CSP with TES

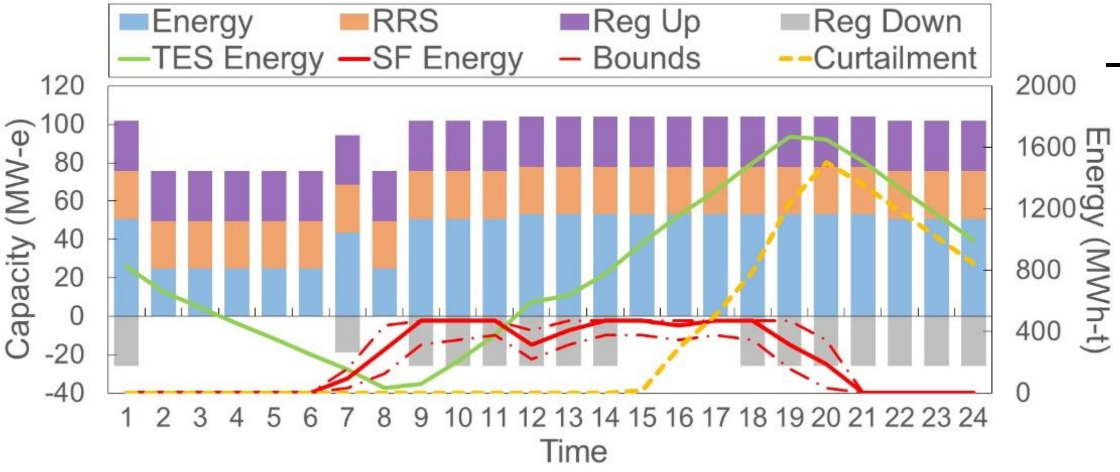
- Motivation
  - The revenues of a concentrating solar power (CSP) plant with thermal energy storage (TES) can be remarkably increased by participating in ancillary service (AS) markets in addition to the energy markets
  - However, offering excessive AS might cause massive curtailment of solar thermal energy and reduce the potential real-time energy revenue
  - Two goals for the CSP plant to coordinate:
    - I: To maximize the profit in the day-ahead markets
    - II: To maintain its capability of solar energy accommodation and revenue potential in real time or the future
- Contribution
  - Introduced a novel index, maximum acceptable curtailment rate, to reflect the trade-offs of CSP plant between providing flexibility to the system and reserving the capability of solar energy accommodation

Offering Strategy for CSP with TES

K=0.1,
Lower MACR



K=0.5,
Higher MACR



	K=0.1	K=0.5
Energy Market Revenue ($)	50,860	48,062
AS Market Revenue ($)	14,842	18,857
Average Hourly RRS (MW-e)	13	25
Average Hourly Reg (MW-e)	29	42
Day-ahead Market Revenue ($)	63,168	64,351
Maximum Potential Curtailment (MW-t)	607	1,504
Potential Real-time Revenue Loss ($)	23,691	58,726

- By properly setting the index, the loss of the potential real-time/future energy revenue is reduced by $35,035, over 55% of the day-ahead revenue
- At a cost of only a $1,183 decrease in the day-ahead market revenue

Publications

Journal:

1. Guannan He, Qixin Chen, etc. Optimal Bidding Strategy of Battery Storage in Power Markets Considering Performance-Based Regulation and Battery Cycle Life. *IEEE Trans on Smart Grid*, vol. 7, no. 5, pp. 2359-2367, 2016.
2. Peng Zou, Qixin Chen, etc. Evaluating the Contribution of Energy Storages to Support Large-Scale Renewable Generation in Joint Energy and Ancillary Service Markets. *IEEE Trans on Sustainable Energy,* vol. 7, no. 2, pp. 808-818, 2016.
3. Guannan He, Qixin Chen, etc. Optimal operating strategy and revenue estimates for the arbitrage of a vanadium redox flow battery considering dynamic efficiencies and degradation. *IET GTD*, vol. 10, no. 5, pp. 1278-1285, 2016.
4. Guannan He, Qixin Chen, etc. Robust Offering Strategy for Concentrating Solar Power Plants in Joint Energy, Reserve and Regulation Markets. *IEEE Trans on Sustainable Energy*, vol. 7, no. 3, pp. 1245-1254, 2016.
5. Guannan He, Qixin Chen, etc. Cooperation of Wind Power and Battery Storage to Provide Frequency Regulation in Power Markets. *IEEE Trans on Power System*. (Under 3rd round of review)
6. Peng Zou, Qixin Chen, etc. Pool Equilibria Including Strategic Storage Units. *Applied Energy*. vol. 177, pp. 260-270, 2016.
7. Peng Zou, Qixin Chen, etc. Electricity markets evolution with the changing generation mix: An empirical analysis based on China 2050 High Renewable Energy Penetration Roadmap. *Applied Energy*, vol. 185, , pp. 56-67, 2017.
8. Qixin Chen, Peng Zou, etc. A Nash-Cournot Approach to Assessing Flexible Ramping Products. *Applied Energy* (submitted).

Conference:

1. Peng Zou, Qixin Chen, etc. Modeling and Algorithm to find the Economic Equilibrium for Pool-based Electricity Market with the Changing Generation Mix. In *PES General Meeting, 2015*, pp.1-5, July 2015.
2. Peng Zou, Qixin Chen, etc. Evaluating the Impacts of Flexible Ramping Products on the Market Equilibrium. In *PES General Meeting, 2016*, pp.1-5, July 2016.

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The End

Thank You!

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